LARGE SCALE DEFORMATION OF THE WESTERN U.S. CORDILLERA

Grant NAG5-11629

Final Report

For the Period 1 February 2002 through 31 October 2002

Principal Investigator

Dr. Richard A. Bennett

December 2002

Prepared for

National Aeronautics and Space Administration
Goddard Space Flight Center, Greenbelt, MD

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

INTRODUCTION

This Project Sumary report summarizes achievements made under NASA grants NAG5-11629. The next section describes our research program, and summarizes our findings. Our specific achievements over the last year are described in the following section.

RESEARCH INVESTIGATIONS

Over the past couple of years, with support from NASA, we used a large collection of data from GPS, VLBI, SLR, and DORIS networks which span the Western U.S. Cordillera (WUSC) to precisely quantify present-day large-scale crustal deformations in a single uniform reference frame. Our work was roughly divided into an analysis of these space geodetic observations to infer the deformation field across and within the entire plate boundary zone, and an investigation of the implications of this deformation field regarding plate boundary dynamics. Following the determination of the first generation WUSC velocity solution, we placed high priority on the dissemination of the velocity estimates. With in-kind support from the Smithsonian Astrophysical Observatory, we constructed a web-site which allows anyone to access the data, and to determine their own velocity reference frame [see http://cfa-www.harvard.edu/spacegeodesy/WUSC/]. Our velocity solution was used in several recent investigations of the southwestern U.S. [Bennett et al., 1999; Shen-Tu et al., 1999; Flesch et al., 2000; Kreemer et al., 2000; Wernicke et al., 2000; Bennett et al., 2002a; Friedrich et al., 2002; Niemi et al., 2002; Melbourne and Helmburger, 2002; Silver and Holt, 2002; Bennett et al., 2002b]. This solution was also used as a "proof of concept" for the viability of PBO [see Fig. 2 of Silver et al., 1998].

The Bennett et al. [1999] results confirmed a number of features previously observed through independent local and very sparse space geodetic studies, including a dominant pattern of right-lateral shear associated with the San Andreas fault, rates of the western-most sites of 46-48 mm/yr relative to a North America reference frame, and some 11-13 mm/yr of extension and shear east of the Sierra Nevada in the Basin and Range Province north of latitude 36N. To the south of 36N, the solution indicated that the southernmost San Andreas fault system accommodates effectively all interplate motion, and that the southern Basin and Range is not deforming significantly. At latitude 37N, the eastern California shear zone (ECSZ) exhibited simple shear oriented ~N40W relative to North America, with a fairly well defined transition zone from localized shear to diffuse spreading in the Basin and Range. Bennett et al. [1999] also reported that the ECSZ-Basin and Range transition region involved a significant component of contraction normal to the overall shear zone trend, with sites in the central Great Basin converging on the ECSZ at a few mm/yr. The orientation of the convergence is in reasonable accord with the Late Cenozoic geologic history of the Death Valley region, which contains numerous northwest-trending folds and other indicators of northeast contraction.

One of our major objectives was to compare estimates of crustal deformation obtained from geology, historical seismicity, and geodesy. These types of data are essential in developing realistic models of seismic hazard, and in linking short-time-scale observations with longer-term geologic processes. Earlier investigations [e.g., Bennett et al., 1998] had suggested, based on the accuracy of the velocity estimates at that time, that contemporary Basin and Range deformation is slow and broadly distributed, rather than being concentrated in the relatively narrow zones of historical earthquakes near the margins of the province. As the accuracy of our results improved, deviations from the average strain-rate model became significant. The largest of these, and the most difficult to explain, was a baseline in north-central Nevada indicating rapid, range-normal crustal shortening at a rate of 2-3 mm/yr in an area where the geology indicates range-normal crustal extension via late Holocene normal faulting [Wernicke et al., 2000]. The disagreement in sign of the geologic velocity field demonstrated that "non-Reidian" behavior may be widespread and detectable using continuous GPS. Wernicke et al. [2000] explored the implications of the conflicting geodetic and geologic data. We found that one possible explanation is that the region of shortening represents the contractile side of a slowly east-propagating deformation pulse generated by the 1915 Pleasant Valley and 1954 Dixie Valley and Fairview Peak earthquakes. Such pulses, which are transient effects not recorded by faulting, are predicted by a broad class of physical models.

These "rate debate" issues were further explored in the Wasatch region along the eastern margin of the Basin and Range. Here there are no sign differences between geologic and geodetic velocity fields, but both are now well enough determined to permit a meaningful quantitative comparison [Friedrich et al., 2002]. We compared present-day deformation rates obtained from space geodesy with geologic displacement rates over at least four temporal windows, ranging from the last millennium up to 10 Myr, for the Wasatch fault and adjacent fault zones. This strain rate across this region is 2-3 times higher than the average contemporary strain rate across the entire province, and coincides with the location of the Wasatch, Oquirrh, and Stansbury normal faults. The vertical component of the displacement rate on the Wasatch fault since 10 Ma were 1.0-1.4 mm/yr from 10 to 6 Ma, slowing to 0.2-0.3 mm/yr averaged over the past 6 Ma. Averaged over the Holocene the rate is 1.5-2.0 mm/yr, but < 0.6 mm/yr averaged over the late Pleistocene. The cumulative vertical displacement record across all three faults also shows time-variable strain release rates ranging from 2-4 mm/yr over the past 10 ka to < 1 mm/yr averaged over the past 130 ka. To be consistent with the apparent change from Pleistocene to Holocene time, conventional earthquake recurrence models would require an accordingly large variation in strain accumulation or loading rate on a 10 kyr time scale, for which there appears to be no obvious geophysical explanation. Rather, clustering on the 10 ka time scale would likely result from complexities in frictional failure laws with relatively constant loading, implying high Holocene strain release rates and comparatively low, uniform strain accumulation rates on the 100 ka time scale. If so, measurements of strain accumulation and strain release may be strongly time-scale dependent for any given fault system, and thus fault offset history and geodetic strain may in general not agree. In Niemi et al. [2001], we investigated whether the observed pattern of broadly distributed strain could, in fact, be due to localized deformation on a small number of faults, as had been suggested earlier by Thatcher et al. [1999] based on modeling of campaign-mode results across the Basin and Range. By compiling known late Quaternary slip rates on normal faults across the region, we found that both fault slip and loading may be relatively evenly distributed on faults throughout the northern Basin and Range.

In Dixon et al. [2002] we also explored the sensitivity of fault slip inferrences based on geodetic data to the models for strain accumulation used. We compared elastic fault-block models to more general descriptions that included the effects of complex crustal and lithospheric rheologies and the earthquake cycle. These investigations led to an exploration of the relative strengths of old (Agua Blanca) and young (San Miguel-Vallacitos) faults. We found that misalignment of the older Agua Blanca fault with Pacific-North America relative plate motion would tend to inhibit slip on this fault unless it were significantly weaker than the younger San Miguel-Vallacitos fault.

In Bennett et al. [2002a], we provided an updated analysis of velocity data for the WUSC region, including a joint analysis of GPS, VLBI, SLR, and DORIS data sets. We explored the sensitivity of the plate boundary deformation field to the analysis technique that we adopted to combine these data sets. In Bennett et al. [2002b], we again updated the WUSC velocity solution by adding several campaign GPS data sets that were previously not used. We used this updated velocity field to estimate the relative motions of the Colorado Plateau (CP), Sierra Nevada-Great Valley (SNGV) microplate, and the central Great Basin (CGB) using GPS data. SNGV-CP motion is 11.4+- 0.3 mm/yr, N47W, whereas SNGV-North America (NA) motion is ~12.4 mm/yr, N47W, slower than previous geodetic estimates, and ~7 counterclockwise from Pacific (P)-NA motion. CGB-CP motion is 2.8+-0.2 mm/yr, N84+-5W, consistent with roughly east-west extension within the eastern Great Basin (EGB). Velocity estimates from the EGB reveal diffuse extension, with more rapid extension of 20+-1 nstr/yr concentrated in the eastern half which includes the Wasatch fault zone, as reported by Friedrich et al. [2001]. SNGV-CGB motion is 9.3+-0.2 mm/yr, N37+-2W, essentially parallel to P-NA motion. Our estimate is significantly slower than previous geodetic estimates for the western Great Basin (WGB), but generally consistent with paleoseismological inferences. The WGB region accommodates N37W directed right-lateral shear at rates of (1) 57+-9 nstr/yr across a zone of width ~125 km in the south (latitude ~36N), (2) 25+-5 nstr/yr in the central region (latitude ~38N), and (3) 36+-1 nstr/yr across a zone of width ~300 km in the north (latitude ~40N). We found that average extension in the direction of WGB shear is 8.6+-0.5 nstr/yr, comparable to average east-west extension of 10+-1 nstr/yr across the northern Basin and Range, but implying a different mechanism of extension. We also found that an alternative model for shear-parallel deformation, in which extension is accommodated across a narrow, more rapidly extending zone which coincides with the central Nevada seismic belt, fits the data slightly better.

NEW ACHIEVEMENTS

The majority of our effort, during this past funding cycle, was to publish new results from two distinct previously NASA supported projects. These include Bennett et al. [2002a], Bennett et al. [2002b], Johansson et al. [2002], Schernick et al. [2002], and Wahr and Davis [2002]. We list all publications that have resulted from this research below.

There have been no reportable inventions or new technology under this grant.

REPORTS PUBLISHED WITH DIRECT SUPPORT FROM NAG5-11629

Bennett, R.A., J.L. Davis, B.P. Wernicke, Present-day pattern of Cordilleran deformation in the western United States, Geology, 27, 371-374, 1999.

Bennett, R.A., J.L. Davis, B.P. Wernicke, and J.E. Normandeau, Space geodetic measurements of plate boundary deformation in the western U.S. Cordillera, in Plate Boundary Zones, e.d. Stein, S.A., J.T. Freymueller, AGU Monograph, 27-55, 2002a.

Bennett, R. A., B. P. Wernicke, N. A. Niemi, A. M. Friedrich, and J. L. Davis, Contemporary strain rates in the northernBasin and Range province from GPS data, Tectonics, in press, 2002b.

Dixon, T., J. Decaix, F. Farina, K. Furlong, R. Malservisi, R. Bennett, F. Suarez-Vidal, J. Fletcher, J. Lee, Seismic cycle and rheological effects on estimation of present-day slip rates for the Agua Blanca and San Miguel-Vallecitos faults, northern Baja California, Mexico, Journ. Geophys. Res., 107, 10.1029/2000JB000099, 2002.

Friedrich, A.M., B.P. Wernicke, N.A. Niemi, R.A. Bennett, and J.L. Davis, Comparison of geodetic and geologic data from the Wasatch region, Utah, and implications for the spectral character of Earth deformation at periods of ten to ten million years, Journ. Geophys. Res., in press, 2002.

Johansson, J.M., J.L. Davis, H.-G. Scherneck, G.A. Milne, M. Vermeer, J.X. Mitrovica, R.A. Bennett, B. Jonsson, G. Elgered, P. Elosegui, H. Koivula, M. Poutanen, B.O. Ronnang, and I.I. Shapiro, Continuous GPS measurements of postglacial adjustment in Fennoscandia, 1. Geodetic results, Journ. Geophys. Res., 107, 10.1029/2001JB000400, 2002.

Niemi, N.A., B.P. Wernicke, A.M. Friedrich, M. Simons, R.A. Bennett, and J.L. Davis, BARGEN continuous GPS data across the eastern Basin and Range province, and implications for fault system dynamics, Geophys. Journ. Int., in press, 2001.

Scherneck H.-G., J. M. Johansson, G. Elgered, J. L. Davis, B. Jonsson, G. Hedling, H. Koivula, M. Ollikainen, M. Poutanen, M. Vermeer, J. X. Mitrovica, and G. A. Milne, BIFROST: Observing the Three-Dimensional Deformation of Fennoscandia, in Glacial Isostatic Adjustment and the Earth System, edited by J. X. Mitrovica and L. L. A. Vermeersen, Geodynamics Series Vol. 29, American Geophysical Union, 69-94, 2002.

Wahr, J., and J. L. Davis, Geodetic Constraints on Glacial Isostatic Rebound, in Glacial Isostatic Adjustment and the Earth System, edited by J. X. Mitrovica and L. L. A. Vermeersen, Geodynamics Series Vol. 29, American Geophysical Union, 3-32, 2002.

Wernicke, B.P., A.M. Friedrich, N.A. Niemi, R.A. Bennett, and J.L. Davis, Dynamics of plate boundary fault systems from the Basin and Range Geodetic Network (BARGEN) and geologic data, GSA Today, 10, 1-3, 2000.
., B. P. Wernicke, N. A. Niemi, A. M. Friedrich, and J. L. Davis, Contemporary strain rates in the northernBasin and Range province from GPS data, Tectonics, in press, 2002b.